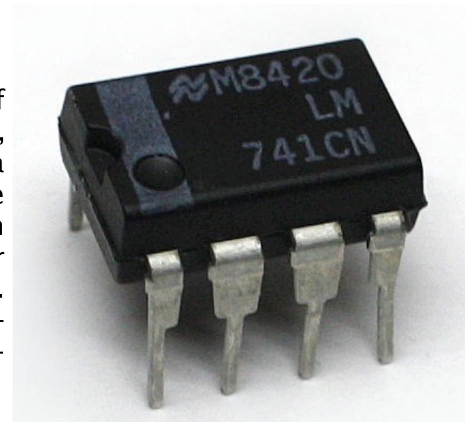
Brass Tacks

An in-depth look at a radio-related topic

Utah Valley Amateur Radio Club
Since Feb. 2016

Operational amplifiers



In many of today's electronic devices and instruments, one of the simplest yet useful components is the operational amplifier, or ***op amp*** for short. It's an analog integrated circuit that does a lot with very little, yet many technicians and engineers alike struggle with just how these little wonders work. Building upon the miracle of the transistor, the op amp represents yet another up-ratchet level of circuit functionality after the basic logic gate. Actually, knowing how an op amp works is not all that important, unless you're attempting to improve upon it, but knowing how to use one is essential to complex analog circuit design.

The term *operational amplifier* should not be confused with a typical radio amplifier unit that you can purchase, plug in, and that can magically reproduce your transceiver's output signal at a higher wattage. Instead, an op amp is used as one of many building blocks in electronic instrumentation (oscilloscopes, signal generators, analyzers, meters), appliances (computers, routers, ham radios, TVs, inverters, controllers, and yes, amplifiers), and much more. In fact, it's no exaggeration to say that op amps can be found in nearly all modern electronic devices.

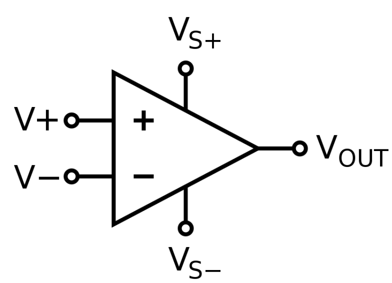
Conversations about op amps and the circuitry that use them can become quite deep in technical theory very quickly, so the goal in this discussion is to highlight its most basic and common properties and applications. To help keep this topic simple, let's focus on three common uses of op amps, that as an amplifier, an oscillator, and an active filter.

Terminology and pinout

Before getting into the details of common usage, let's agree on some terminology. Because an op amp is a *differential amplifier* (amplifies the difference between the two input signals), it has no inherent sense of a "ground" and is supplied by two voltages, often labeled **V_s+** and **V_s–**, also known as the ***positive supply rail*** and ***negative supply rail***, respectively.

Amplification is the increase in some value (voltage, in the op amp case) of a particular signal. ***Gain*** (often labeled ***A*** or ***G***, depending on who describes it) is the measure of amplification, defined as the ratio of the output voltage to the input voltage. ***Saturation*** is the condition in which an amplifier can no longer increase the voltage past a maximum, defined by the supply rails and other properties.

The diagram to the right shows the basic "pinout" of a typical op amp; that is, the connections on the outside of the device and what they connect to internally. The **V_s+** and **V_s–** pins are the supply rails, as mentioned previously. The **V+** pin is the *non-inverting input voltage*, while the **V–** pin is the *inverting input voltage*. **V_{OUT}** is the single output of the op amp. (An op amp with a differential input and a differential output is called a *fully differential amplifier*, which is outside the scope of this discussion.)



Op amp symbol and pinout

Brass Tacks

continued

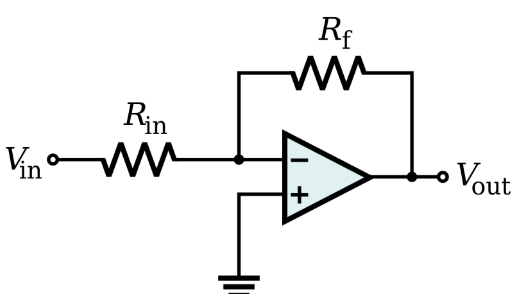
Closed-loop amplifier

If a connection is made between the op amp output and one of its inputs, we say that the op amp is operating in *closed-loop* mode; otherwise, it's operating in an *open-loop* fashion. Due to the enormous gain of an op amp, the open-loop amplifier is easily driven to saturation, and so is not often as useful as in the closed-loop mode, as will be shown later.

Perhaps the most common configuration in which an op amp is used in a circuit is known as ***negative feedback***, so-called because the circuit outside the op amp has provided the device with some electrical path from its output to its inverting (**V–**) input. In this mode, the op amp will attempt to do what's necessary electrically to bring the inverting (**V–**) and non-inverting (**V+**) voltages to very close to the same value. Since in this mode the measured voltage is common (the same) between the two, this is known as the *common mode*, and the two input voltages the input *common-mode voltage*. This is not to be confused with the common-mode that arises from an extra current flowing on the skin of a conductor, detailed in another discussion.

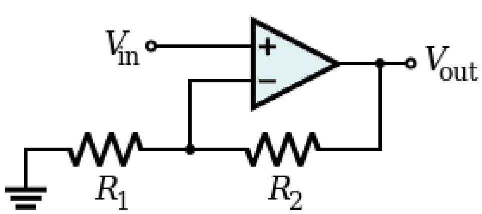
When examining a circuit or design that includes an op amp, one of the first things that should be determined is whether the op amp is configured for negative feedback. If negative feedback is used, several fairly reasonable assumptions can be made, which can greatly simplify op amp behavior calculations. Perhaps the most important of these assumptions is that the voltages of the **V+** and **V–** inputs are nearly the same, the minute difference between the two known as *input offset voltage*.

The two most useful op amp negative feedback circuits are those for an *inverting amplifier* and a *non-inverting amplifier*. The following is a schematic example of a inverting amplifier, and the accompanying voltage gain calculation, given the resistor values:



$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

The following is an example of a non-inverting amplifier and its voltage gain calculation:



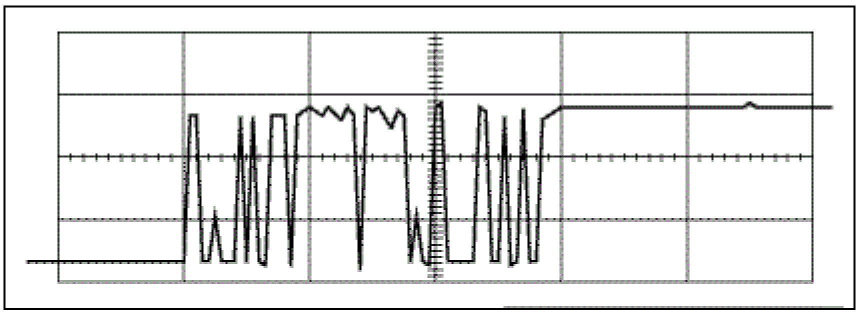
$$V_{out} = (1 + \frac{R_2}{R_1}) V_{in}$$

Brass Tacks

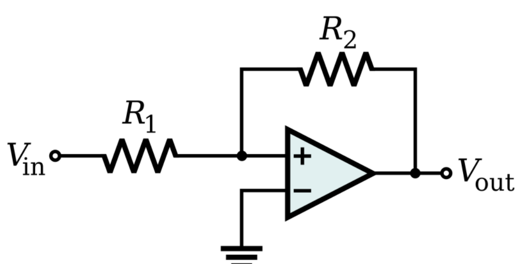
continued

An op amp circuit using ***positive feedback*** in its closed loop can be useful due to its high gain; that is, the output is at maximum (saturation) positive when the input is even a little positive, and at maximum negative when the input is even a little negative.

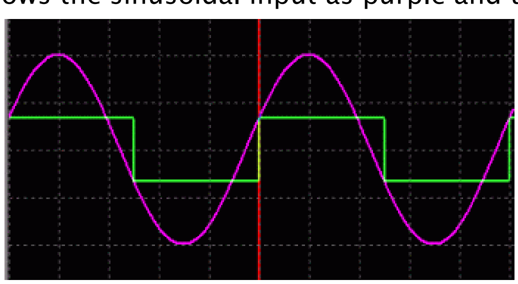
Take the example of a *switch de-bouncer*. When a physical switch closes, it doesn't simply make perfect contact once and is done; it "bounces" closed, meaning that it can make contact dozens of times before settling into its final closed position, which can wreak havoc on a circuit that might not tolerate multiple rapid openings-and-closings of the switch. Here's a graph showing an actual switch closing:



If this was the input to a digital circuit, then the switch has created an unwanted stream of false ones and zeroes (and a few unknown transitions) into the circuit, which can confuse it. (Opening the switch has the same result, of multiple openings and closings before settling.) A switch de-bouncer can be made from an op amp using positive feedback configured in a circuit known as a *Schmitt trigger*, which uses *hysteresis* to achieve its effect, and is shown here:



The Schmitt trigger using an op amp with positive feedback can also be useful for converting a sinusoid into a square wave, with the upper and lower voltage bounds (common-mode output voltage) establishing the "high" and "low" voltage levels required by digital circuits. The following oscilloscope display shows the sinusoidal input as purple and the digital output as green:



Brass Tacks

continued

The ideal op amp

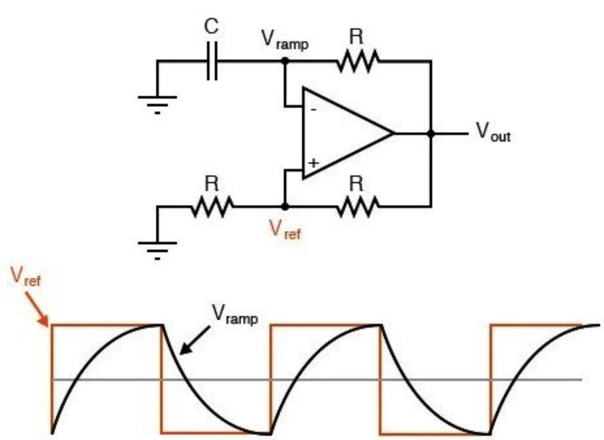
The concept of an ideal op am is important for analog engineering design work, because these assumptions not only simplify otherwise difficult calculations, but are also closely reflective of actual op amp behavior. Here are some useful ideal op amp properties:

- **Very high (infinite) input impedance**, and therefore zero input current
- **Very low (zero) output impedance**, and therefore an infinite output current range
- **Infinite gain**
- **Zero input offset voltage** (difference between the two input voltages)
- **Infinite slew rate** (*dV/dt*), a measure of how quickly the voltage can change
- Others, including infinite bandwidth, zero phase shift, and zero noise

Obviously, none of these can be perfectly realized physically, due to finite material properties and limited manufacturing processes, but often close is good enough. Where more precise engineering is required, equivalent (resistive, capacitive, inductive) properties can be used to supplement the ideal model.

The op amp as an oscillator

Using the RC time constant of the input capacitor and feedback resistor in the following circuit, the op amp can be made into an oscillator:



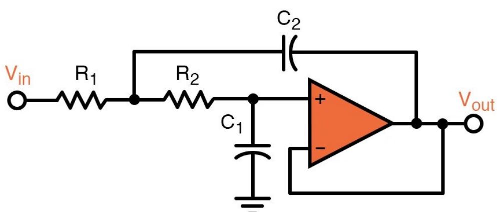
When the output is saturated positive, the V_{ref} point will be positive, and the capacitor will charge in the positive polarity. When V_{ramp} reaches and exceeds V_{ref} by the smallest amount, the output will then immediately saturate negative due to the high gain of the op amp, and the capacitor will charge in the negative polarity. Oscillation occurs because the positive feedback is nearly instantaneous, and the negative feedback is delayed by the RC time constant. The oscillation frequency can then be adjusted by varying the size of the capacitor and / or feedback resistor.

Brass Tacks

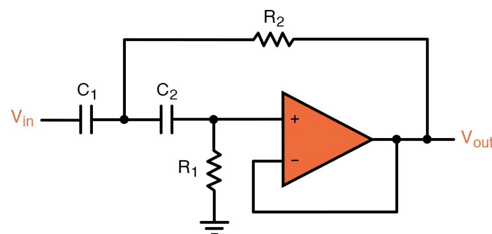
continued

The op amp as an active filter

In past articles, we've discussed general filtering and filters made from components, but those were primarily passive filters, ones made from passive components. It turns out that much of the filtering involved in amateur radio equipment is by *active filtering*, which often uses op amps as the core filtering control mechanism. The following two filters are examples of second-order active filters:



2nd order low-pass filter



2nd order high-pass filter

Finally

We've only discussed the simplest or most common op amp properties. Other important design considerations include, but are not limited to, gain bandwidth product, slew rate, and input noise voltage. Additionally, here are other useful op amp circuits that find uses in instrumentation and amateur radio equipment:

- comparator - open-loop (no signal being fed back to the input) configuration, in which the output is simply the difference between the two input signals, multiplied by the gain
- buffer (voltage follower) - changes circuit impedance without changing the voltage
- integrator - the output signal reflects the integral of the input
- differentiator - the output signal reflects the differential of the input
- exponential output - the output signal reflects the exponential of the input
- logarithmic output - the output signal reflects the logarithm of the input
- gyrator - can produce the effect of an inductor, using a capacitor and an op amp

Summary

The op amp (operational amplifier) is an integrated circuit electronic component that can be externally wired to provide a variety of useful functions. It can be found in most of today's electronics, and modern amateur radio could not implement many of its important features without them. By employing negative feedback, the op amp can be used as an amplifier with configurable gain. In many cases, calculations can be simplified under certain configurations if the op amp is assumed to be ideal. Other significant op amp uses include the oscillator and active filter.

Noji Ratzlaff, KNØJI (kn0ji@arrl.net)